Chapter 11

Red Giant Evolution

Life on the main sequence is characterized by the stable burning of hydrogen to helium under conditions of hydrostatic equilibrium.

- While the star is on the main sequence the inner composition is changing, but there is little outward evidence until about 10% of the hydrogen is exhausted.
- Then the star experiences a (relatively) rapid series of changes that take it away from the main sequence.
- Stellar evolution after the main sequence is of short duration relative to the main sequence.
- However, post main-sequence evolution is generally more complex than main-sequence evolution.

Accordingly, let us now turn to a discussion of post main-sequence evolution.

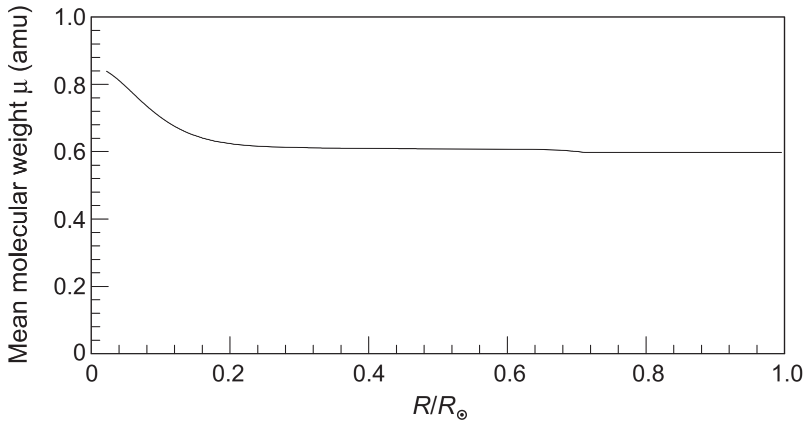


Figure 11.1: Mean molecular weight for the Sun from the Standard Solar Model.

11.1 Evolution Away from the Main Sequence

While the star burns hydrogen in near-perfect hydrostatic equilibrium on the main sequence, a series of internal changes sets the stage for the star's subsequent evolution.

- As hydrogen fuses to helium the mean molecular weight of the plasma in the core is increased:
  - Complete conversion of hydrogen to helium increases the molecular weight by a factor of $\frac{8}{3}$.
  - Solar models indicate that the mean molecular weight of the core has increased from ~ 0.61 amu at ZAMS to ~ 0.85 amu now (Fig. 11.1).
  - This reduction of the particle number in the core of the star lowers the pressure in the energy-generating zone, causing the core to contract, raising temperature and density.

- The rise in the core temperature increases the temperature gradient dT/dr, leading to an increased flow of energy from the star.
  - The outer layers of the star expand in response.
  - This causes an increase in the luminosity and radius, and a decrease in the surface temperature.
- Because of these changes, the star begins to develop a high-density core surrounded by an extended, diffuse envelope with low surface temperature—it becomes a red giant.
- If the star is massive enough, rising core temperatures and densities can ignite successively higher mass fuels and initiate a series of advanced burning stages.

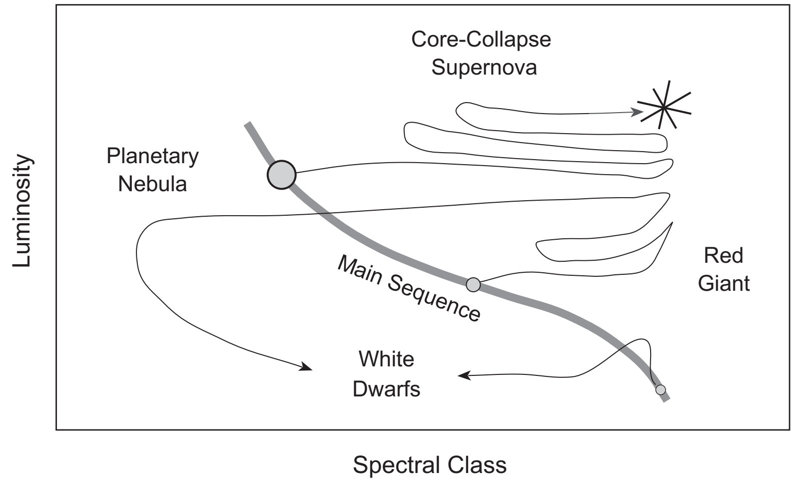


Figure 11.2: Categories of stellar evolution after the main sequence.

Depending on mass, these steps can lead to the three qualitative scenarios that are sketched in Fig. 11.2.

- *Lowest mass main-sequence stars ($M \lesssim 0.5 M_\odot$):* core temperatures never rise high enough to ignite the helium produced by proton burning and the star evolves to a helium white dwarf.
- *Intermediate mass stars ($0.5 \lesssim M \lesssim 8 M_\odot$):* evolution produces a red giant that eventually sheds much of its outer envelope and becomes a carbon–oxygen or neon–magnesium white dwarf.
- *The most massive stars ($M \gtrsim 8 M_\odot$):* evolution from the main sequence leads to a sequence of burning episodes involving successively heavier fuels until the core of the star becomes gravitationally unstable and produces a core-collapse supernova.

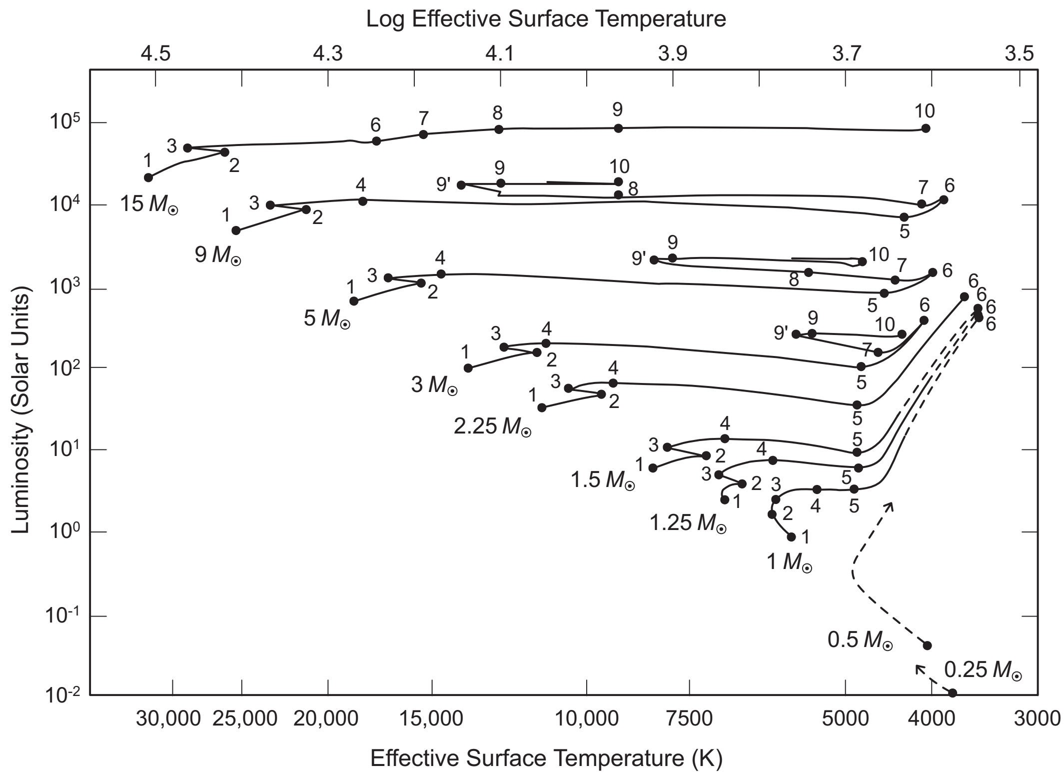


Figure 11.3: Evolution off the main sequence for stars of different initial main-sequence mass.

An overview of initial evolution after leaving the main sequence for various initial main-sequence masses is given in Fig. 11.3. In this chapter we address the post main-sequence fate of intermediate mass stars. The fate of more massive stars will be examined in later chapters.

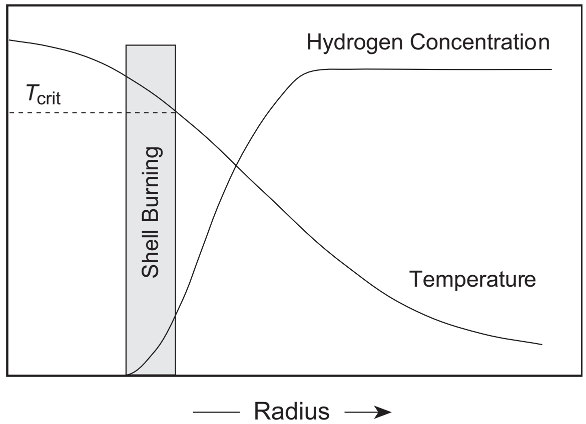


Figure 11.4: Conditions for hydrogen shell burning.

11.2 Shell Burning

An important aspect of post main-sequence evolution is the establishment of *shell burning sources* (Fig. 11.4).

- As the initial core hydrogen is depleted, a thermonuclear ash of helium builds up in its place.
- This ash is inert at hydrogen fusion temperatures because much higher temperatures and densities are necessary to initiate helium fusion.
- However, as the core becomes depleted in hydrogen there remains a concentric shell in which the hydrogen concentration and the temperature are both sufficiently high to support hydrogen fusion (Fig. 11.4).

This is termed a *hydrogen shell source.*

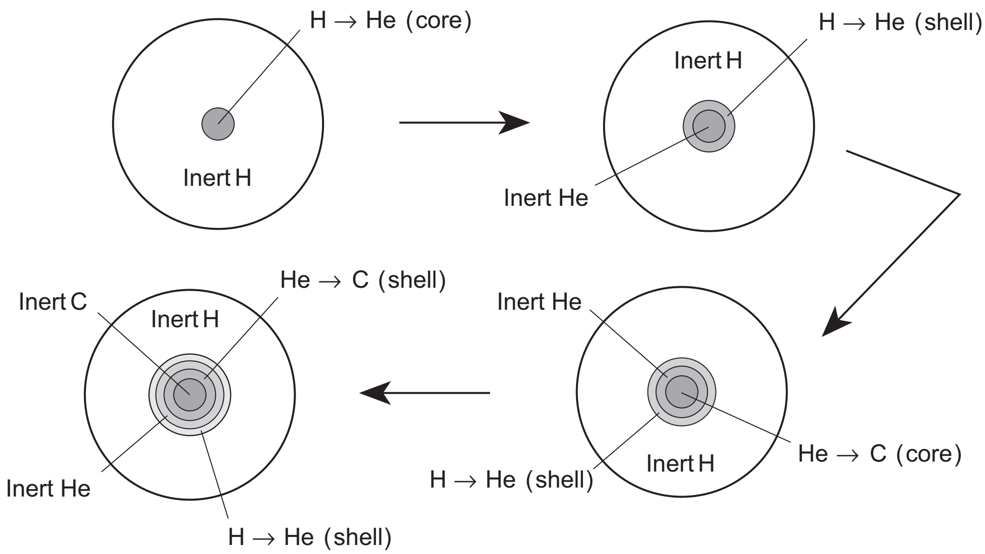


Figure 11.5: Schematic illustration of successive shell burnings.

As the core contracts after exhausting its hydrogen fuel, the temperature and density rise and this may eventually ignite helium in the core.

- As helium burns in the core a central ash of carbon is left behind that is inert because much higher temperatures are needed to fuse it to heavier elements.
- This is termed core helium burning.
- Just as for hydrogen, once sufficient carbon ash has accumulated in the core, helium burning will be confined to a concentric shell around the inert core.
- this is termed a *helium shell source.*

If the star is massive, this scenario may be repeated for successively heavier core and shell sources (Fig. 11.5).

The shell and core sources described above are not necessarily mutually exclusive.

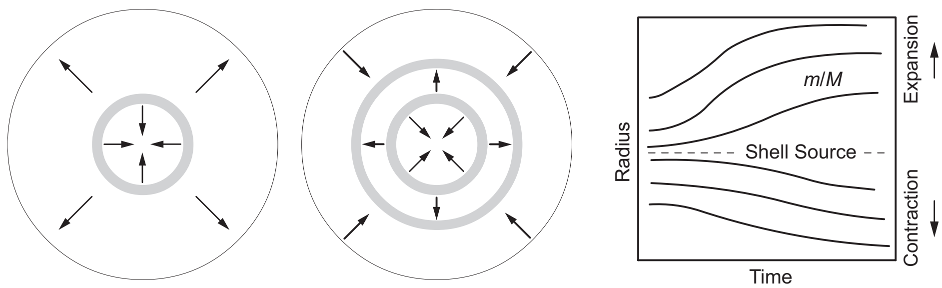
- For more massive stars there may exist at any particular time
  - only a core source,
  - only a shell source,
  - multiple shell sources, or
  - a core source and one or more shell sources

  burning simultaneously.
- These sources can have complicated instabilities and interactions.

An important concept for understanding the action of shell sources is the *mirror principle*, which we now describe.

Mirror Response of Mass Shells: One important aspect of stellar evolution with shell energy sources is termed the *mirror principle*.

- Extensive experience with stellar evolution simulations indicates that *shell sources tend to produce "mirror" motion of mass shells above and below them,* as illustrated in the figure below.



(a) Shell source (b) Two shell sources (c) Separation of mass shells by a single shell source.

- For example, if there is a single shell source the mass layers below the shell source tend to contract and the mass layers above the shell source tend to expand, as illustrated in (a) and (c).
- For two shell sources, each tends to mirror the mass shells above and below, as illustrated in (b).
- In the absence of core burning, with two shell sources the core tends to contract, so by the mirror principle the layers above the inner shell source tend to expand (moving the second shell source further outward).
- Applying the mirror principle to the outer shell source, the layers outside the outer shell source (surface layers, for example) will tend to contract.

Detailed motion in the HR diagram in late stellar evolution simulations often can be predicted by this principle of mirrored motion.

11.3 Stages of Red Giant Evolution

Globular clusters have HR diagrams differing substantially from those for stars near the Sun or for open clusters.

- We have interpreted this provisionally as evidence that *globular clusters are old* and that
- these differences are connected with the *time evolution of star populations.*
- We are now in a position to place those qualitative remarks on a much firmer footing.
- The most distinctive features of the HR diagrams for old clusters are
    1. The absence of main-sequence stars above a certain luminosity, and
    2. Loci of enhanced populations in the giant region termed the
        - *red giant branch* (RGB),
        - the *horizontal branch* (HB), and
        - the *asymptotic giant branch* (AGB),

        respectively.

These are illustrated schematically in Fig. 11.6 and for an actual cluster in Fig. 11.7.

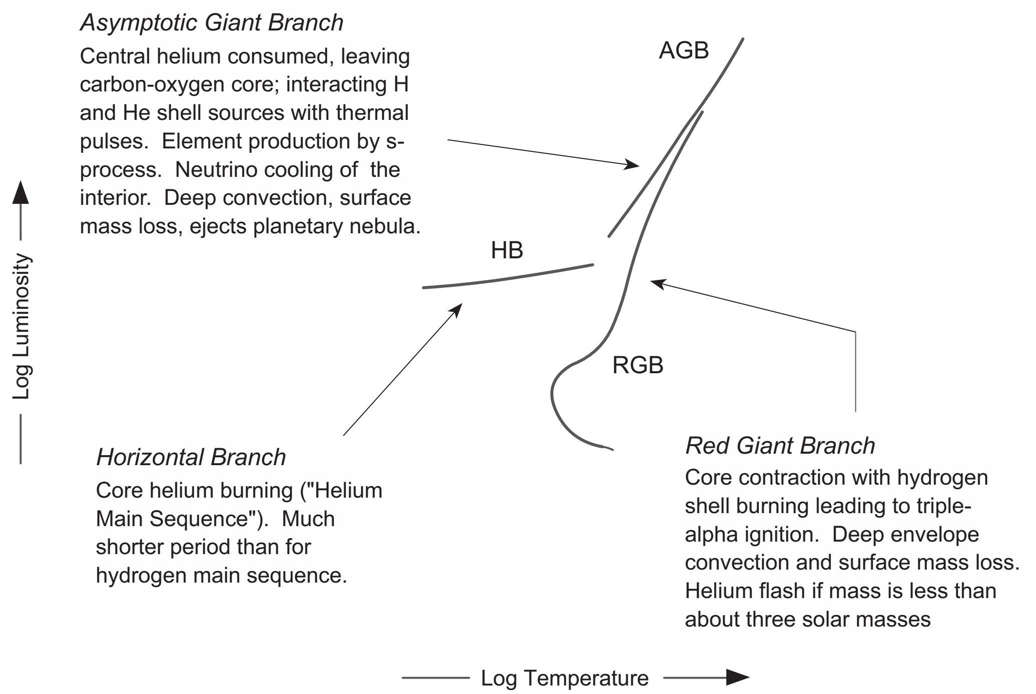


Figure 11.6: Schematic giant branches in an evolved cluster.

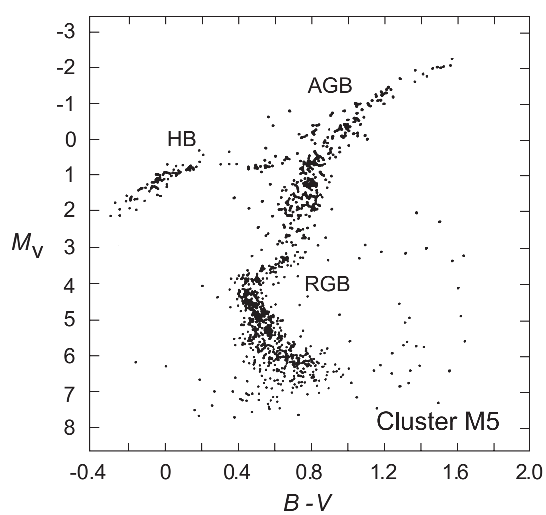


Figure 11.7: Actual giant branches for the globular cluster M5 in Serpens.

- Regions of enhanced population in the HR diagram are a signal that individual stars spend significant portions of their lives in these regions.
- As we now discuss, the
  - red giant branch,
  - horizontal branch, and
  - asymptotic branch

  can be identified with distinct stages of post main-sequence evolution for intermediate mass stars.
- These stages are of short duration compared with main-sequence evolution, but are long compared with stages in between.

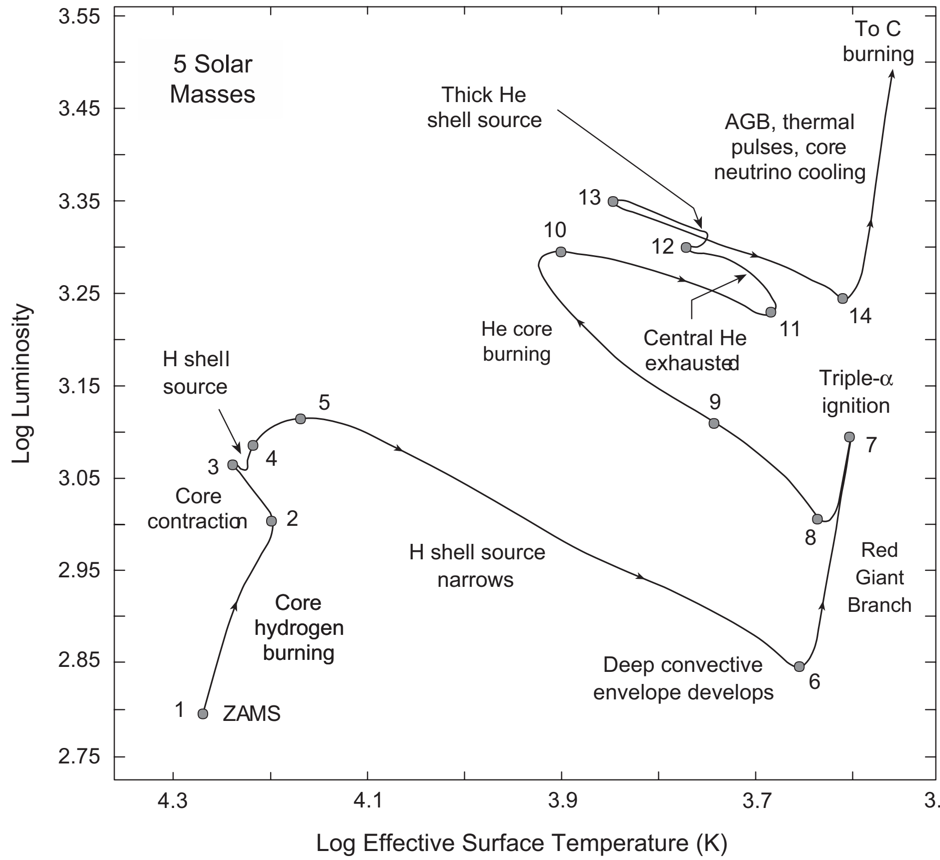


Figure 11.8: Evolution away from the main sequence for a 5 solar mass star.

As representative, we consider the calculated evolution of a 5 solar mass star, as illustrated in Figs. 11.8 and 11.9.

- Beginning at the ZAMS the star converts hydrogen to helium.
- This causes a very small upward drift on the HR diagram.
- As core hydrogen is depleted the core contracts and eventually a hydrogen shell source is established.

These events signal the advent of a rapid departure from the main sequence that we will now follow in some detail.

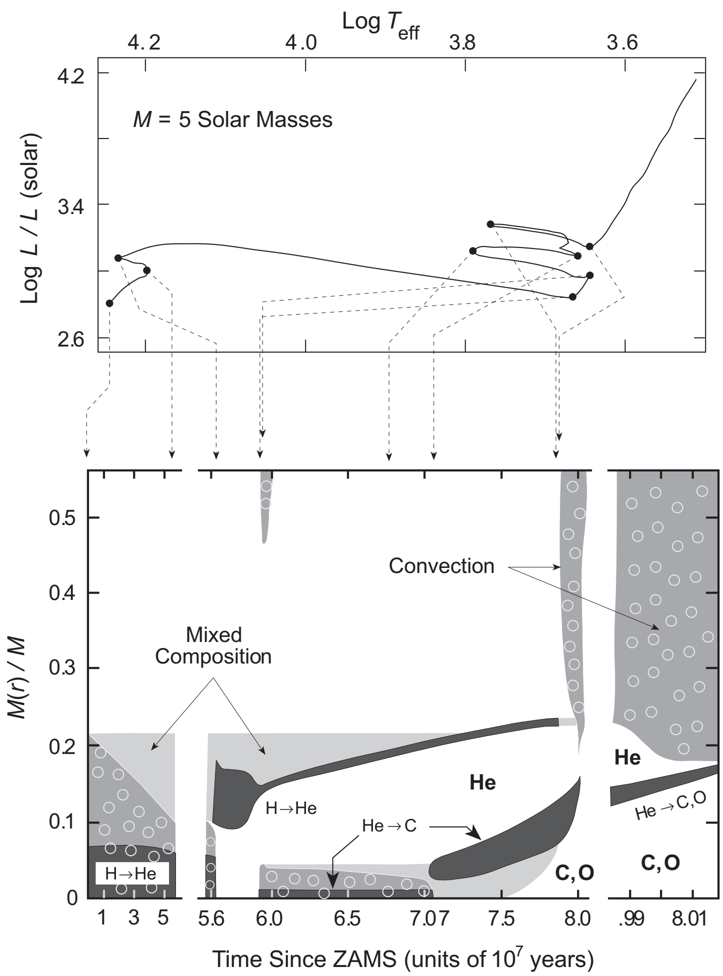


Figure 11.9: Post main-sequence evolution of a 5 solar mass star. Darkest shading indicates regions of energy production and regions with circles are convective. Note the breaks in scale for the time axis.

11.4 The Red Giant Branch

Over time the hydrogen shell source established when the core hydrogen is depleted burns outward, leaving behind a helium-rich ash.

- Because the sole thermonuclear energy source at this point is in a concentric shell, the core cannot maintain a thermal gradient and it equilibrates in temperature.

> Such *isothermal cores* are characteristic of stars that have only shell energy sources.

- As the core increases in size because of the shell burning it is supported primarily by the pressure of the helium gas, which is typically still nondegenerate and nonrelativistic.
- But there is a limit to the mass of an isothermal helium core that can be supported against gravity by the gas pressure. This *Schönberg–Chandrasekhar limit* is given by (see Exercise 11.1)

$$M_c \simeq 0.37 \left(\frac{\mu_{\rm env}}{\mu_c} \right)^2 M,$$

  for an isothermal core of ideal helium gas, where M is the total mass of the star, M_c is the mass of the isothermal core, μ_c is the mean molecular weight in the core, and $\mu_{\rm env}$ is the mean molecular weight in the envelope.

> Growth of an isothermal helium core to this size typically requires that about 10% of the original hydrogen be burned, which is the basis for the earlier statement that significant evolution from the main sequence commences when 10% of hydrogen has been consumed.

When the Schönberg–Chandrasekhar limit is reached in the core it can no longer support itself, or the layers above, against gravity.

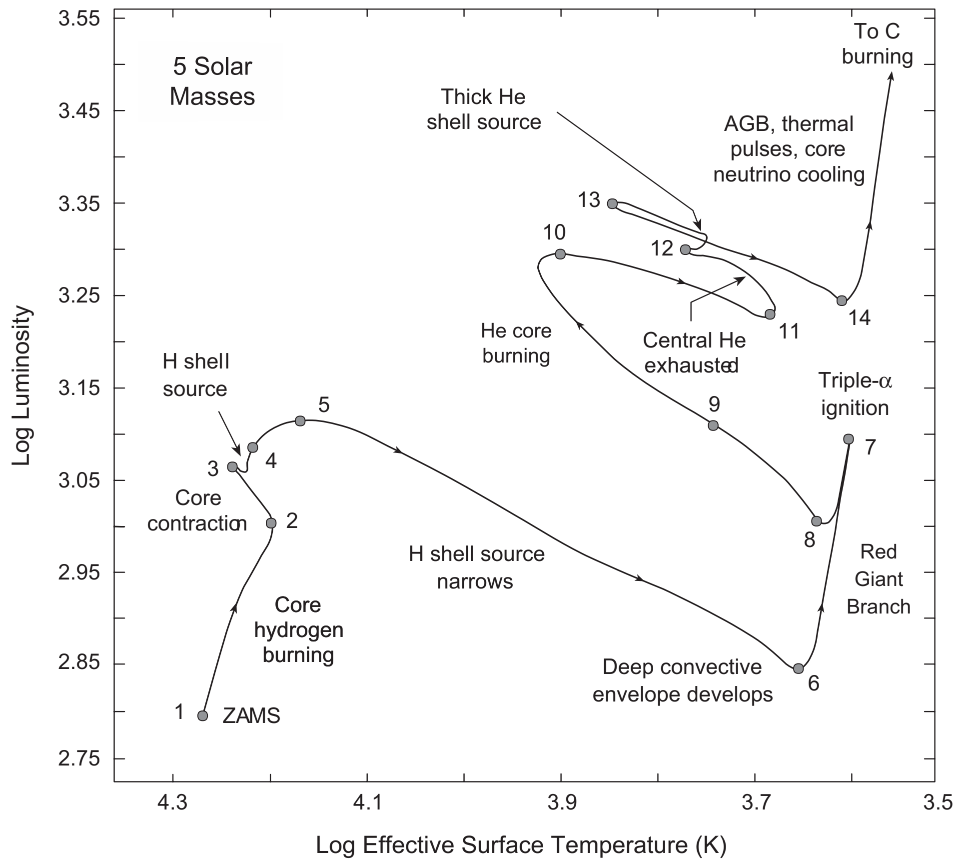
- It begins to collapse on a *Kelvin–Helmholtz timescale,* which is
  - slow compared to the dynamical timescale but
  - rapid compared to the nuclear burning timescale that has governed the time spent on the main sequence.

- The collapse continues until
  - ignition of helium fusion in the core provides a stabilizing pressure, or
  - until interior densities are reached where the electron gas becomes degenerate.

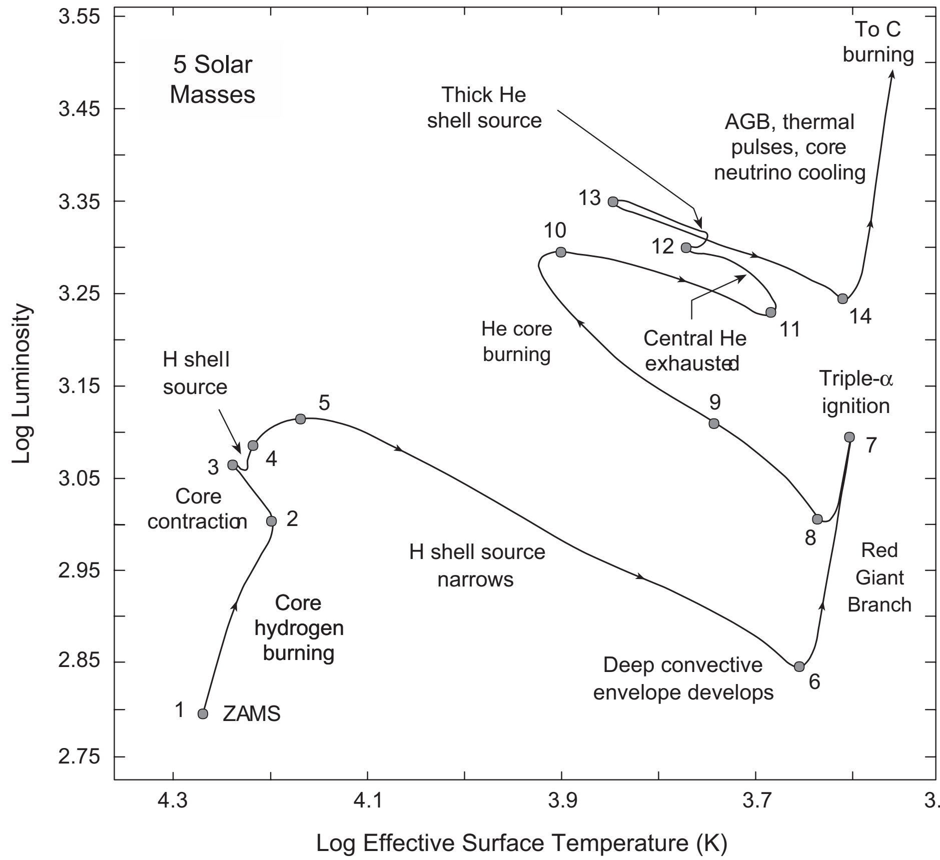
- Provided that the core mass does not exceed about $1.4\ M_\odot$, the degeneracy pressure stops the collapse, but only after the core has become much hotter and denser, and substantial gravitational energy has been released.

- Much of the energy released in the collapse is deposited in the envelope, which expands and cools, enlarging and reddening the photosphere.

- Thus the star evolves rapidly upward and to the right relative to the main sequence into the red giant region of the HR diagram.



- The region between the main sequence and the RGB (roughly between points 5 and 6 in the figure above) contains few stars and is called the *Hertzsprung gap*. The star evolves so rapidly through this region that there is little chance of observing it in the Hertzsprung gap.
- As the temperature of the envelope decreases, opacity increases and the temperature gradient exceeds the adiabatic gradient.
- Thus the star becomes convective in much of its envelope.

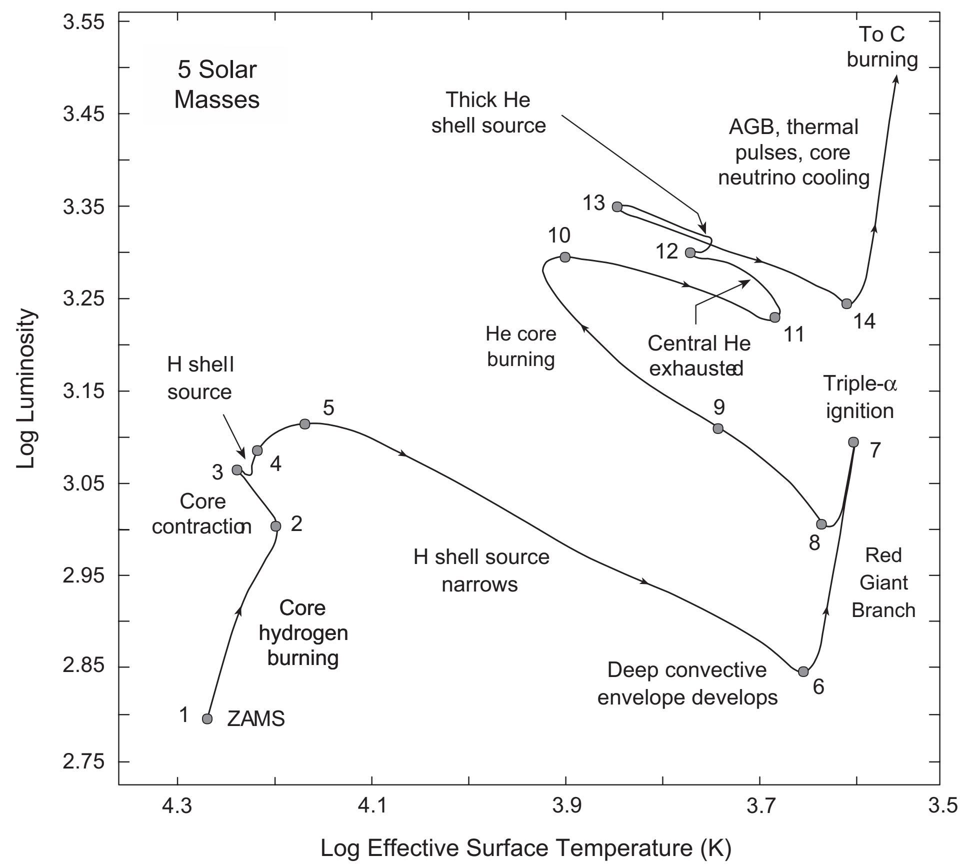


- We may then view the evolution to the red giant region as something like the inverse of the collapse of fully convective protostars to the main sequence.

- The almost fully convective star climbs the Hyashi track in reverse to the red giant region.

- The corresponding evolution in the above figure is on the red giant branch between the points labeled 6 and 7.

- While on the red giant branch the greatly-expanded star can exhibit significant envelope mass loss, with rates as large as $10^{-6} M_\odot$ per year observed for RGB stars.



11.5 Helium Ignition

- The triple-α reaction will be triggered when the core temperature reaches about 0.8×10^8 K.
- The onset of helium burning corresponds to the cusp shown in the above figure at point number 7, and signals the end of red giant branch evolution.
- The ignition of the core helium is qualitatively different for stars above and below about $3M_\odot$, as we now elaborate.

As discussed earlier, high mass stars generally have higher core temperatures than low mass stars at all stages of their evolution.

- Calculations indicate that stars of about $6M_{\odot}$ or more have high enough central temperatures to evolve all the way to helium burning without their cores becoming degenerate.
- Under these conditions, the commencement of core helium burning is probably a rather smooth and orderly process.
- On the other hand, calculations indicate that for stars of about $3M_{\odot}$ or less the core electrons will have become highly degenerate before the triple-α sequence ignites.
- The equations of state for ideal gases and degenerate gases differ fundamentally in the relationship between temperature and pressure:
  - For an ideal gas the pressure is proportional to temperature.
  - For a degenerate gas the *pressure is essentially independent of the temperature,* because it derives from the Pauli principle, not thermal motion.

11.5.1 Thermonuclear Runaways under Degenerate Conditions

Ignition of thermonuclear reactions under degenerate conditions leads to violent energy releases:

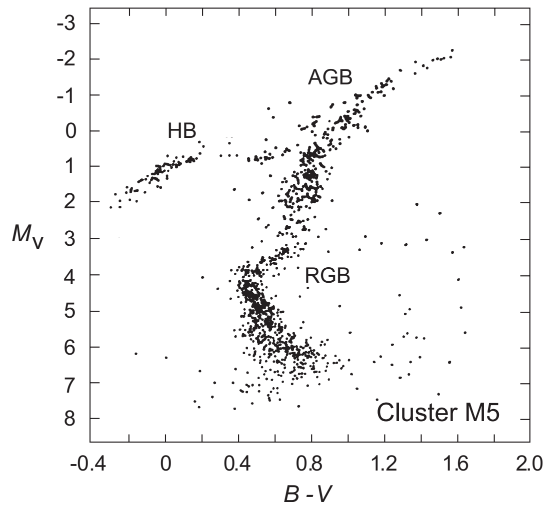
1. Ignition of the fusion reaction releases large amounts of energy, which quickly raises the local temperature.
2. In a normal explosion (ideal gas), a rise in temperature causes a corresponding rise in pressure that separates and cools the reactants, limiting the explosion.
3. Not so in degenerate gases because pressure is not increased initially by the sharp temperature rise.
4. Since charged-particle fusion reactions have very strong temperature dependence, the rise in temperature causes a rapid increase in the reaction rates and the fusion reactions run faster.
5. This in turn raises the temperature further and thus reaction rates, and so on *(thermonuclear runaway)*.
6. The large thermal conductivity of degenerate matter means a thermonuclear runaway triggered locally spreads rapidly through the degenerate matter.
7. This runaway continues until enough electrons are excited to lift the degeneracy of the electron gas.
8. The equation of state then tends to that of an ideal gas and the resulting increase of pressure with temperature moderates the reactions.

11.5.2 The Helium Flash

When such a thermonuclear runaway occurs under degenerate conditions for triple-α it is termed a *helium flash*.

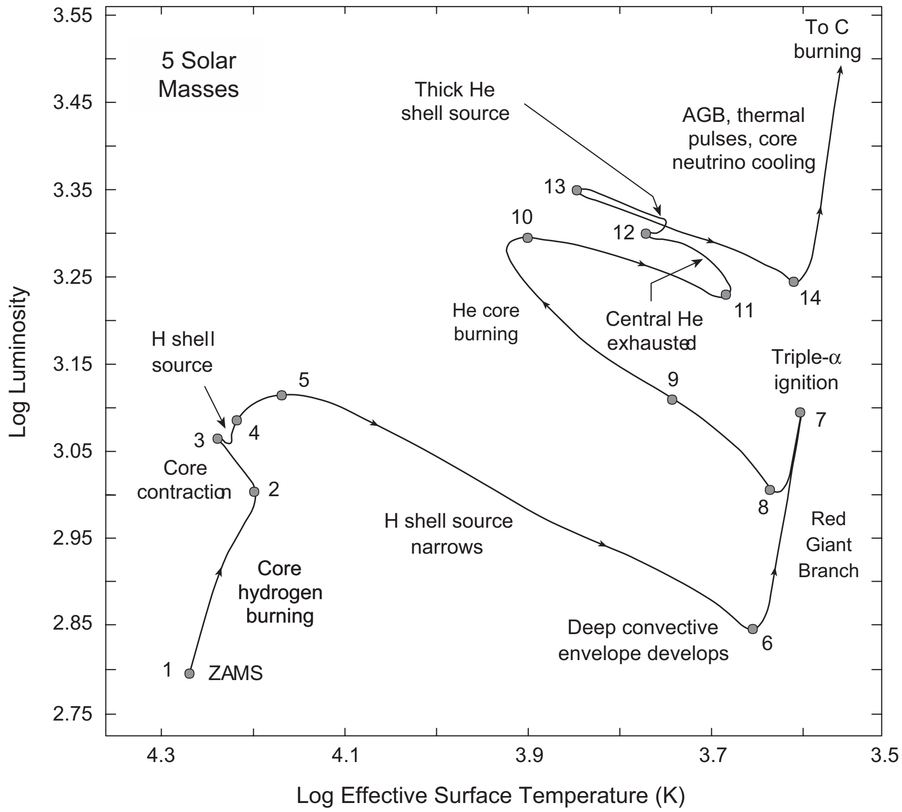
- Simulations show that stars of less than about 3 solar masses that ignite helium burning will probably do so under degenerate conditions.
- Simulations indicate further that the helium flash
  - ignites the entire core of the star within seconds,
  - that the temperature can rise to more than 2×10^8 K before the runaway begins to moderate, and that
  - the energy release during the short flash can approach 10^{11} solar luminosities (comparable to the luminosity of a galaxy!).
- However, these simulations also indicate that this extremely violent event probably has little directly visible external effect because the enormous energy release is almost entirely absorbed in the envelope.
- In effect, the explosion is so strongly tamped by the external matter in the gravitational potential well of the star that it does not make it to the exterior.

- Once the degeneracy of the core is lifted following the helium flash (or following the onset of the triple-α reaction in heavier nondegenerate cores), the helium burns steadily to carbon at a temperature of about 1.5×10^8 K.
- This signals the beginning of the horizontal branch (HB) portion of red giant evolution.



11.6 Horizontal Branch Evolution

- The horizontal branch (HB) of the above figure corresponds to a period of stable core helium burning that is in many ways analogous to the core hydrogen-burning main sequence.
- Thus, this period is often termed the *helium main sequence*.



- The HB corresponds to points 8–10 above.
- This "helium-burning main sequence" is a time of hydrostatic equilibrium for the same reasons as for the hydrogen-burning main sequence.
- The helium-burning main sequence is much shorter than the hydrogen-burning main sequence, in accord with earlier discussion of burning timescales.
- Initially on the horizontal branch the star typically has lower luminosity than in the preceding RGB period, but higher than when it was on the main sequence.

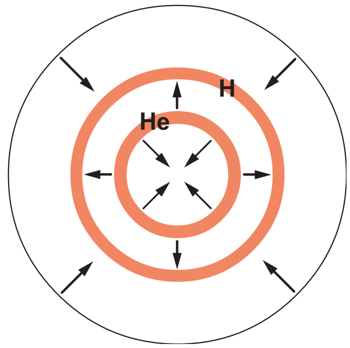
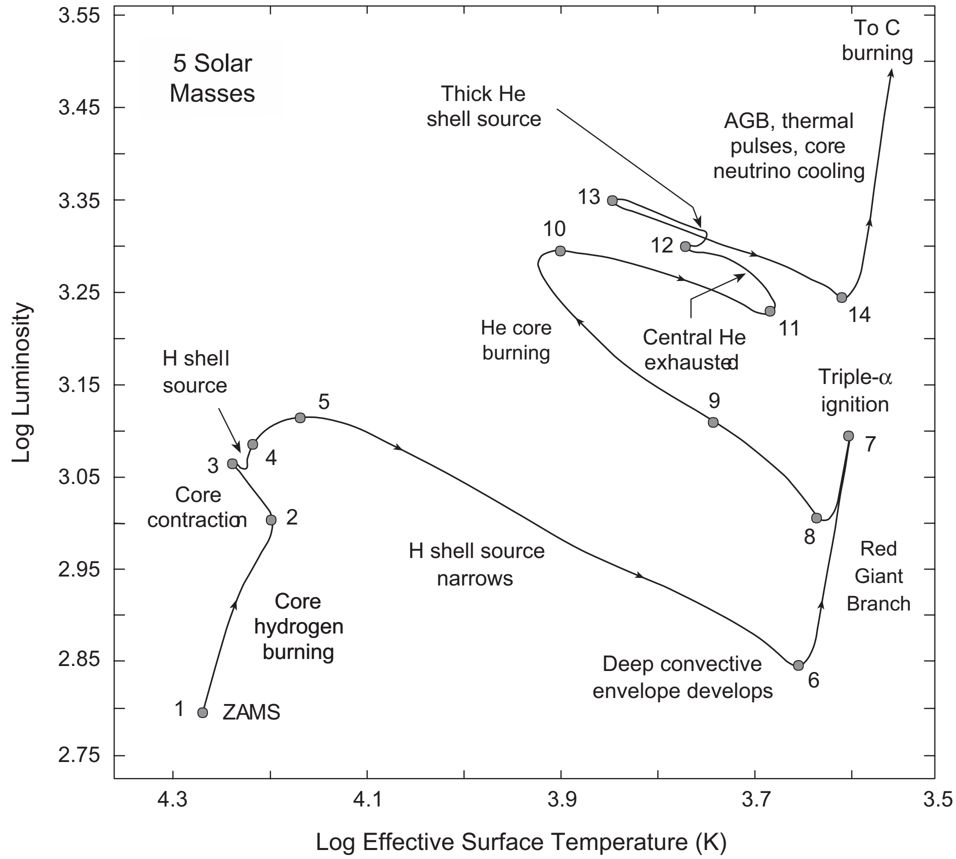
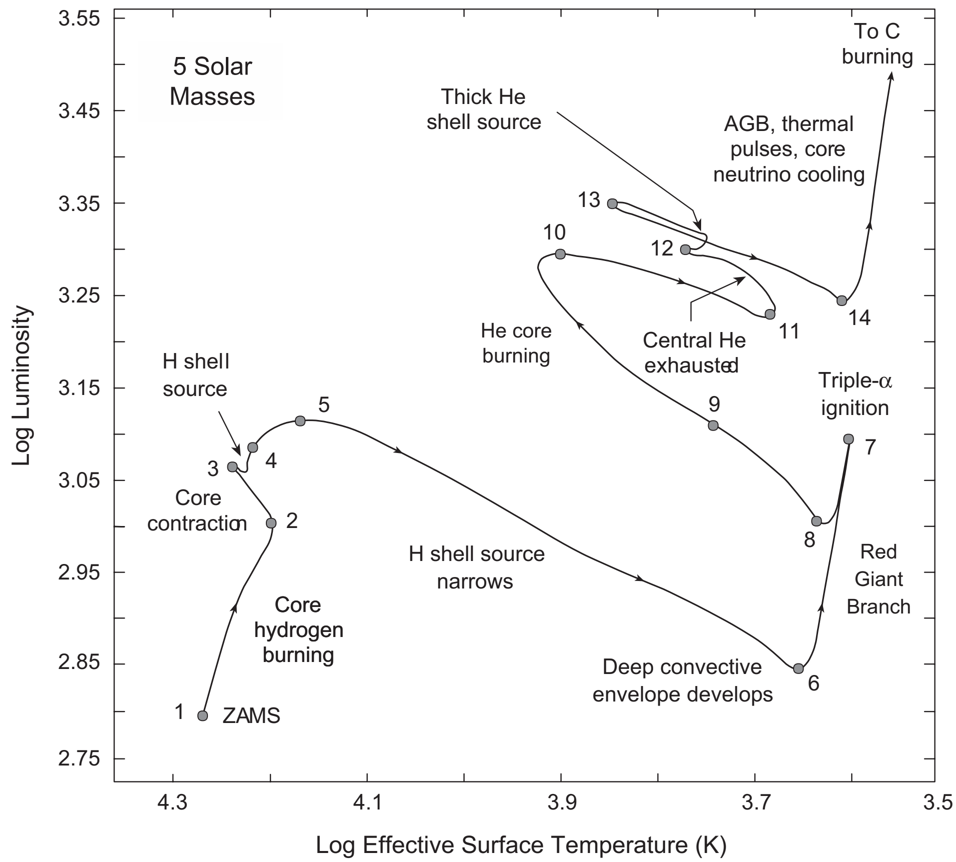


Figure 11.10: Mirror principle applied to helium and hydrogen shell sources in horizontal-branch evolution.

- The star remains on the horizontal branch as long as there is helium fuel in its core to burn. When the core helium is exhausted, the core contracts and a thick helium burning shell is established.
- The star now has *two shell sources:*
  - the broader helium-burning shell and
  - the thin hydrogen-burning shell lying above it.
- Mirror principle (see Fig. 11.10:
  - the inert core inside the helium source contracts (no power source),
  - the inert helium layer outside the helium shell source expands, pushing the hydrogen shell source to larger radius, and
  - the outer layers of the star contract.



- This causes the star to move left on the HR diagram and represents the evolution between points 11 and 13 in the above figure.
- The helium shell source narrows and strengthens as the core compresses further.
- Layers above the helium shell source expand and cool, which turns off the hydrogen shell source that was burning above the helium shell source, leaving only a single active shell source.



- In accordance with the mirror principle, the star contracts inside the helium source and expands outside it, drifting quickly to the right in the HR diagram until it reaches the vicinity of the Hyashi track (point 14 above).
- This signals the transition to the asymptotic giant branch (AGB).

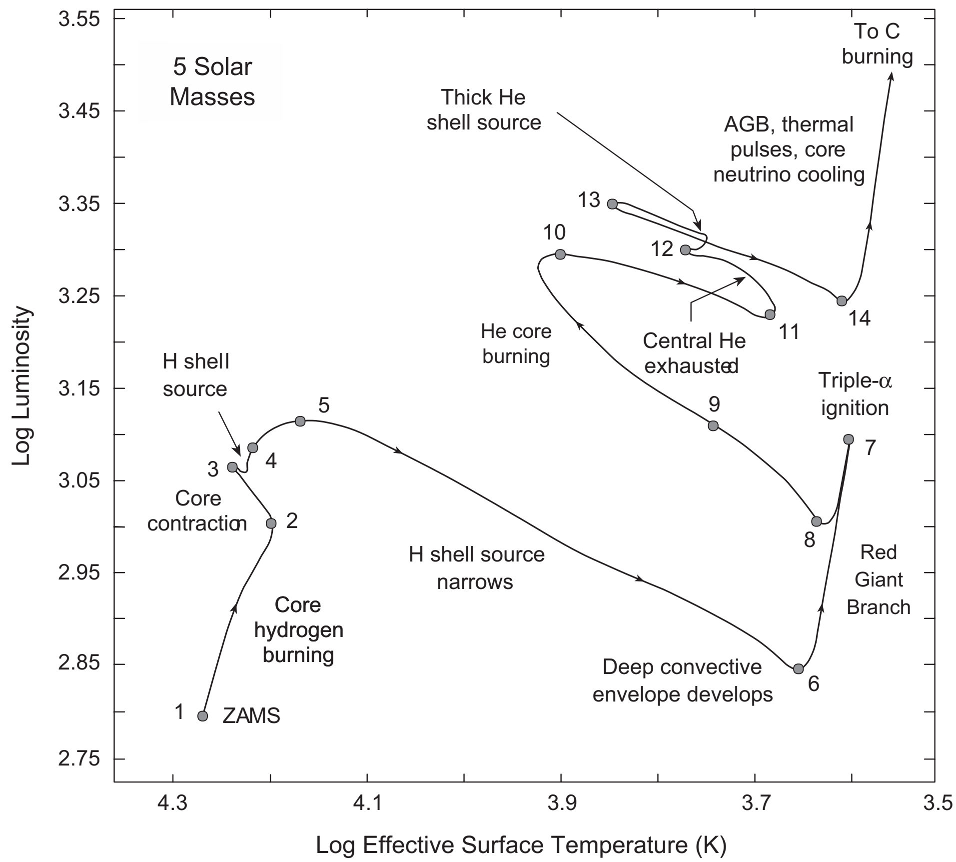
11.7 Asymptotic Giant Branch Evolution

In many respects the evolution on the AGB now mimics that following the establishment of the first hydrogen shell source after core hydrogen was depleted on the main sequence.

- However, the star now has
  - an electron-degenerate C–O core and
  - two shell sources rather than one.

  (The hydrogen source turned off after ignition of the helium shell source but it will re-ignite after early evolution on the asymptotic giant branch.)

- The star again increases in luminosity and radius and moves into the red giant region as earlier, but at even higher luminosities on the asymptotic giant branch.



- The corresponding evolution in the above figure is from point 14 and beyond.
  - Roughly: continuation of the ascent on the RGB along the Hyashi track that was interrupted by ignition of the core helium source that stabilized the star for a time on the horizontal branch.
  - If the star is massive enough, the growing carbon core may ignite eventually, but if $M \lesssim 4-5M_\odot$ this is not likely and all subsequent energy production will be from the shell sources.

A number of important features characterize asymptotic giant branch evolution:

1. The shell sources exhibit instabilities called *thermal pulses.*
2. Shell sources in AGB stars are thought to be the primary site for the slow neutron capture or *s-process.*
3. Stars in the giant region often exhibit large surface mass loss. This is particularly true for AGB stars.
4. Deep convective envelopes that form in the AGB phase can dredge elements synthesized in the interior up to the surface, where they can be distributed to the interstellar medium by winds from the surface.

Let us discuss each of these important aspects of asymptotic giant branch evolution in more depth.

11.7.1 Thermal Pulses

The AGB period is characterized by the presence of both *hydrogen and helium shell sources.*

- However, these shell sources exhibit
  - instabilities
  - a complex interrelationship

  such that at any one time often only one of the two shell sources is burning.
- These instabilities are called *thermal pulses* or *helium shell flashes.*
- It can be shown on rather general grounds that a thin shell source is inherently unstable:
  - Basically one finds that if shell sources are narrow enough the temperature *increases* upon expansion.
  - This is strongly destabilizing and sets the stage for a thermonuclear runaway.

Therefore, in many respects a thin shell source behaves like a degenerate gas with regard to thermal stability, even if the gas in the shell source is non-degenerate.

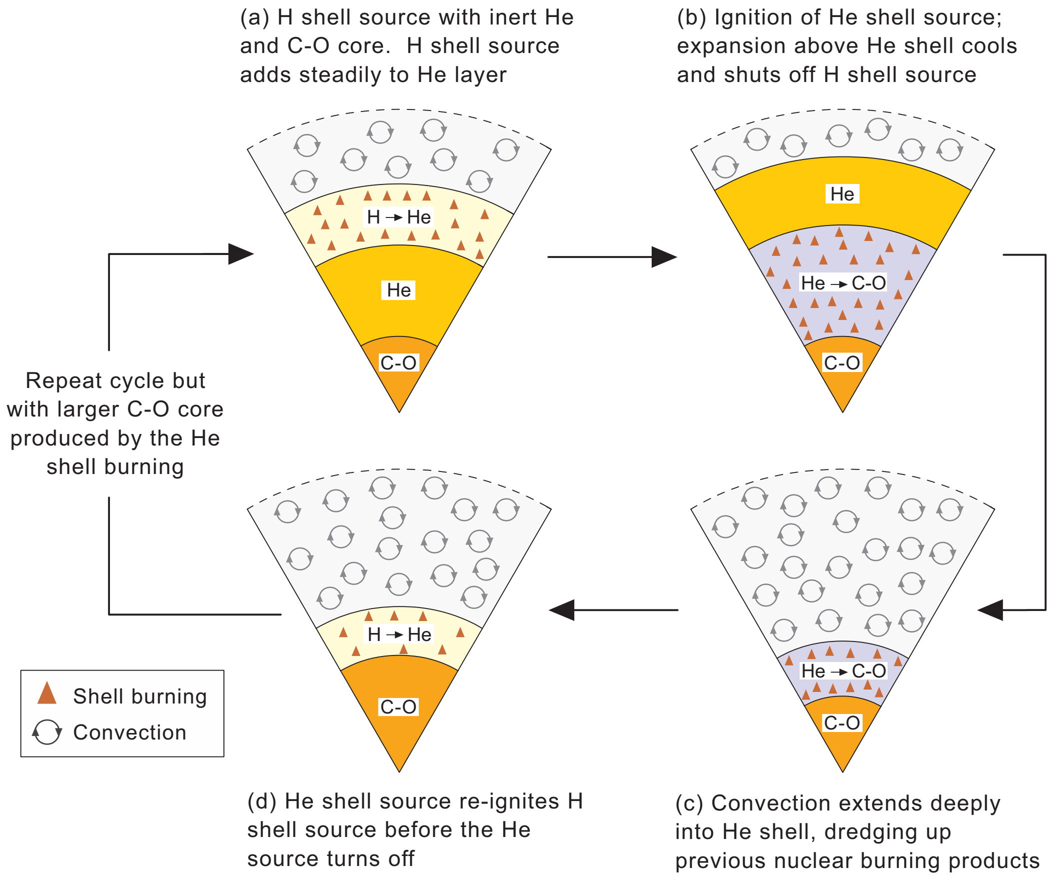
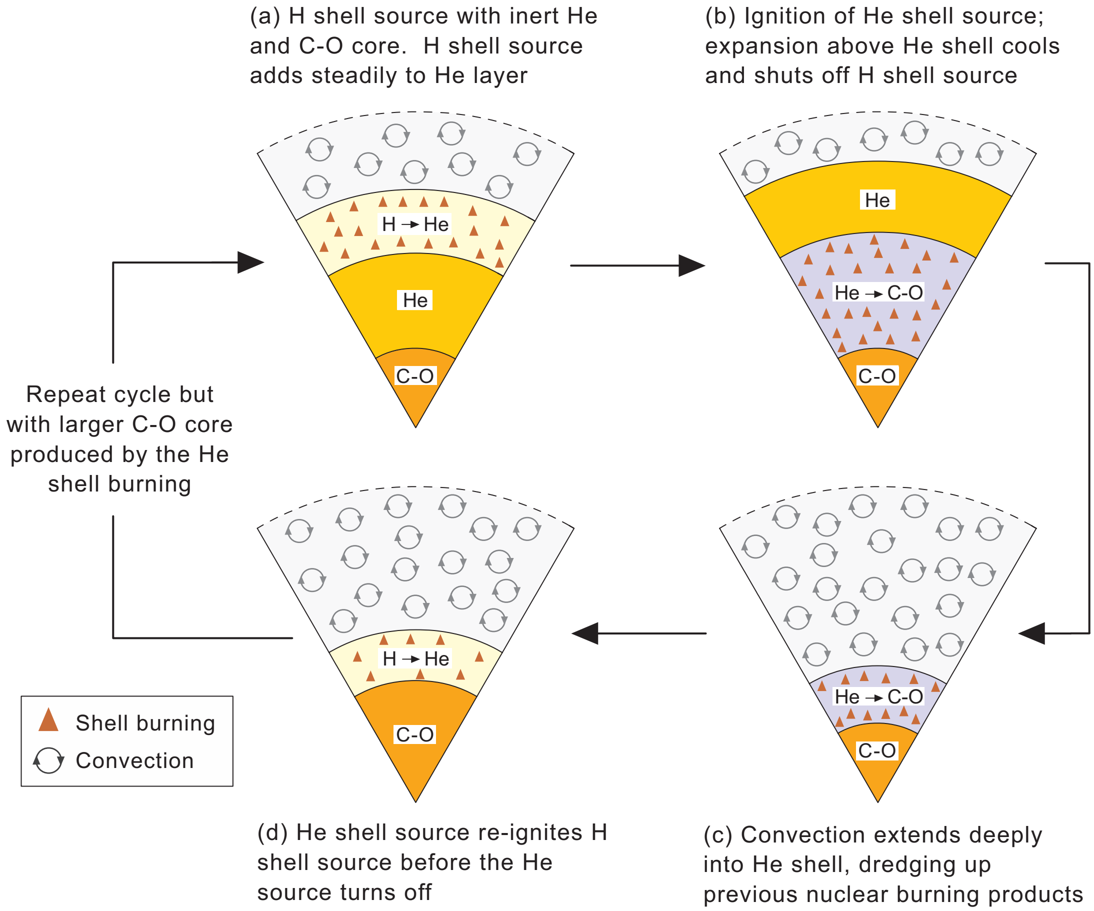


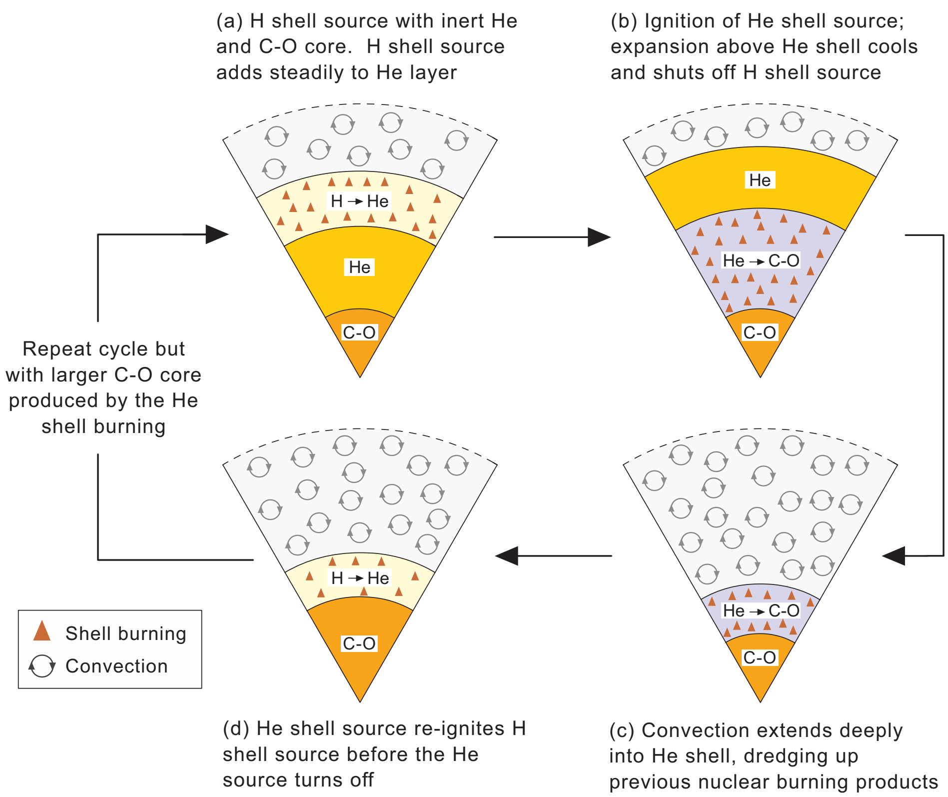
Figure 11.11: Schematic illustration of thermal pulses in an AGB star.

AGB thermal pulses are illustrated in Fig. 11.11.

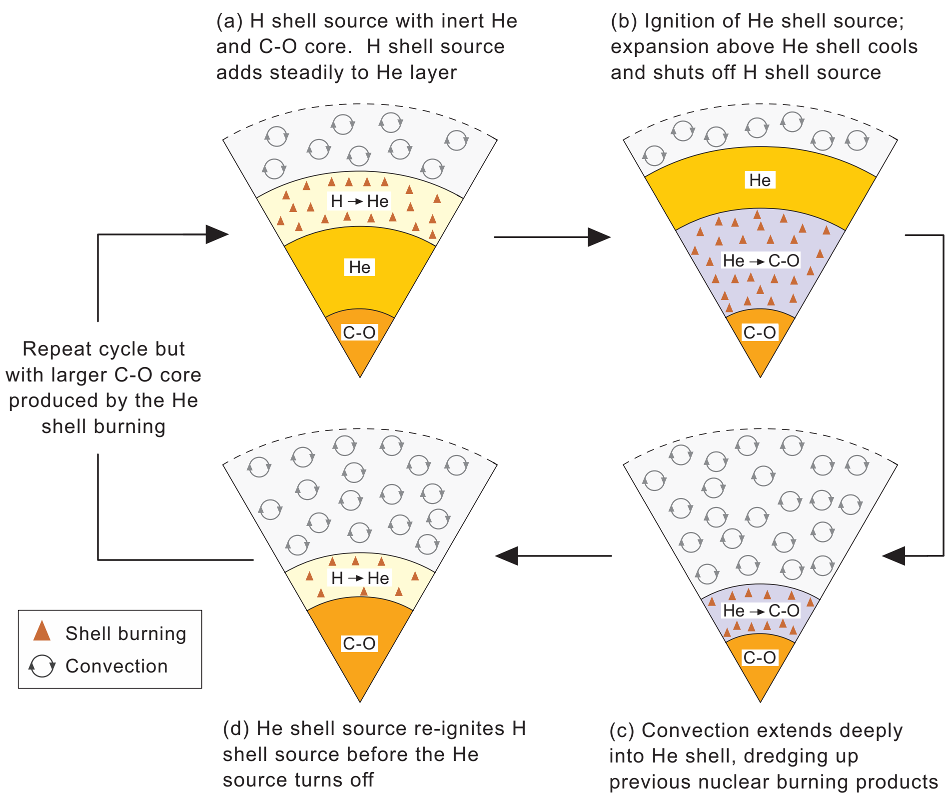
- Let us assume that we have initially an inert C–O core surrounded by an inert He layer, with a hydrogen shell source at the base of the hydrogen layer above adding to the He layer (Fig. 11.11(a)).



- As the core compresses the base of the helium layer may ignite, giving an inner He shell source and an outer H shell source.
- Expansion of layers above the hot He shell source lowers the temperature enough at the base of the hydrogen envelope to turn off the H shell source, leaving the star with a single He shell source (Fig. (b)).



- The hot helium shell source produces a steep temperature gradient and convection develops that reaches down to the vicinity of the He shell source, as illustrated in Fig. (c).
- This convection mixes burning products from earlier evolution into the surface layers.
- The He shell source burns outward, leaving a growing C–O core behind.



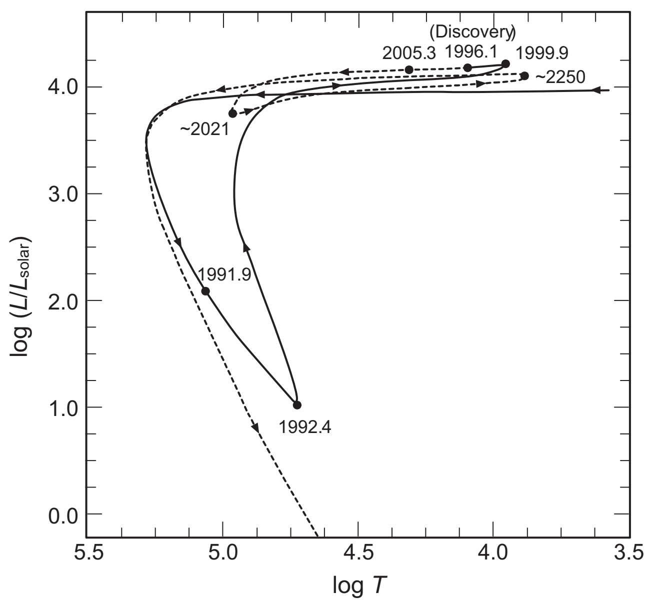
- The He shell source eventually extinguishes because of insufficient temperature at larger radius, but not before the proximity of the hot He source re-ignites the shell source at the base of the hydrogen layer, leading to the situation in Fig. (d).
- The hydrogen shell source burns outward, leaving behind a new layer of helium and the cycle is repeated, but now with a larger carbon–oxygen core.

Simulations indicate that an AGB star can undergo many such thermal pulses (tens to hundreds of pulses before the envelope is eroded away by mass loss).

- The thermal pulse durations typically are only 10^4–10^5 years (a tiny fraction of the life of an average star).
- Thus it is very difficult to catch a star undergoing thermal pulses.
- About a quarter of AGB stars are predicted to undergo one final helium shell flash after hydrogen burning has ceased.
- This late thermal pulse occurs after the star has ejected most of its envelope as a planetary nebula and is settling into the white dwarf phase.
- Computer simulations of this event suggest that in such a star the helium shell can re-ignite and the small remaining H envelope can be convectively mixed into the helium shell, leading to additional rapid hydrogen-driven flash burning and renewed mass ejection.
- Late thermal pulse events in asymptotic giant branch stars are expected to be rare, with a predicted rate of only about *one per decade in our galaxy.*

The star V4334 Sgr (Sakurai's Object) is thought to be a star caught undergoing a late thermal pulse.

- Since its discovery in 1996, it has exhibited very rapid evolution on the HR diagram accompanied by substantial mass ejection.
- Model simulation of the evolution of Sakurai's object on the HR diagram is illustrated in the following



  with a solid line indicating the prediction for evolution before discovery and a dashed line afterwards.

- These predicted loops imply surface-T variations by factors of 10 on timescales of 10–100 years.
- The observed surface T increased by about a factor of 2 in just the 10 years following discovery in 1996.

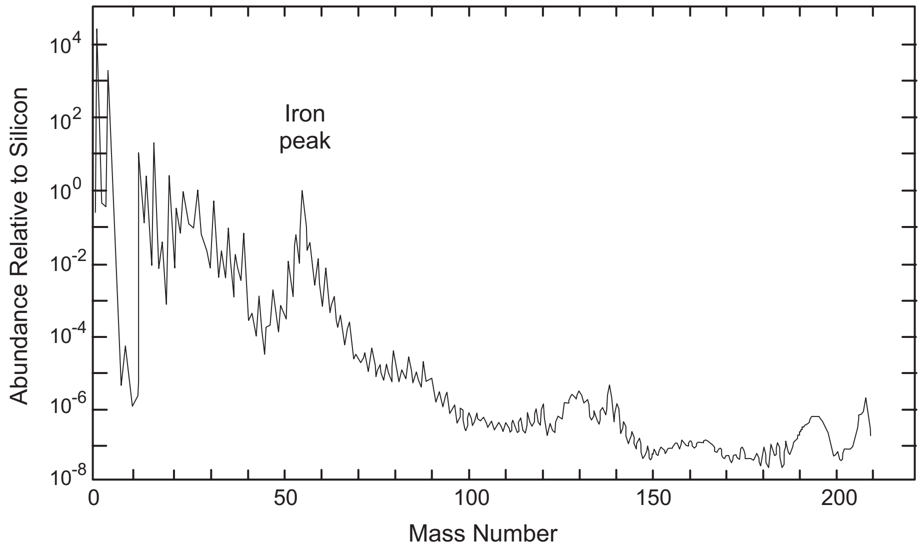


Figure 11.12: Solar System elemental abundances relative to silicon abundance.

11.7.2 Slow Neutron Capture

Figure 11.12 summarizes observed elemental abundances.

- Elements up to iron can be produced by fusion reactions and by nuclear statistical equilibrium in stars.
- Elements beyond Fe can't be produced in the same way because the Coulomb barriers become so large that extremely high temperatures are required.
- These high temperatures would produce a bath of high-energy photons that would photodisintegrate any heavier nuclei that were formed.
- Thus other mechanisms produce heavier elements.

One possibility is the capture of neutrons on nuclei to build heavier nuclei.

- Because neutrons are electrically neutral they do not have a Coulomb barrier to overcome.
- This permits reactions to take place at low enough temperatures that the newly-formed heavy nuclei will not be dissociated immediately by high-energy photons.
- There are two basic neutron capture processes that are thought to produce heavy elements:
  - the slow neutron capture or *s-process* and
  - the rapid neutron capture or *r-process*.
- Astrophysical sites for these neutron capture reactions have not been confirmed, but it is widely believed that
  - the s-process takes place in AGB stars
  - the r-process takes place in core-collapse supernova explosions.

We shall discuss the s-process here and will address the r-process in later chapters.

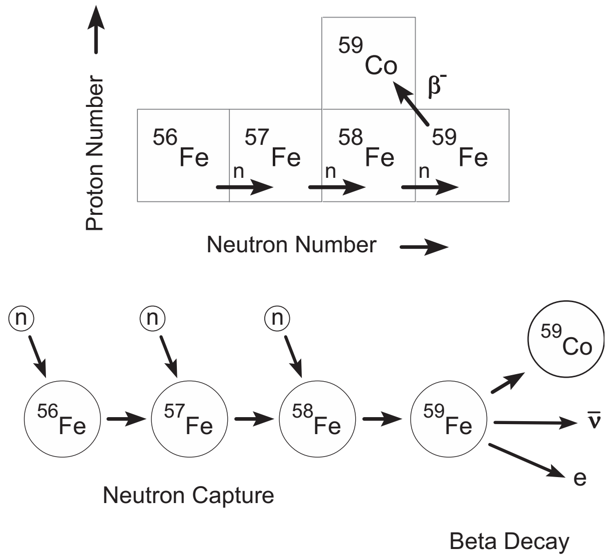
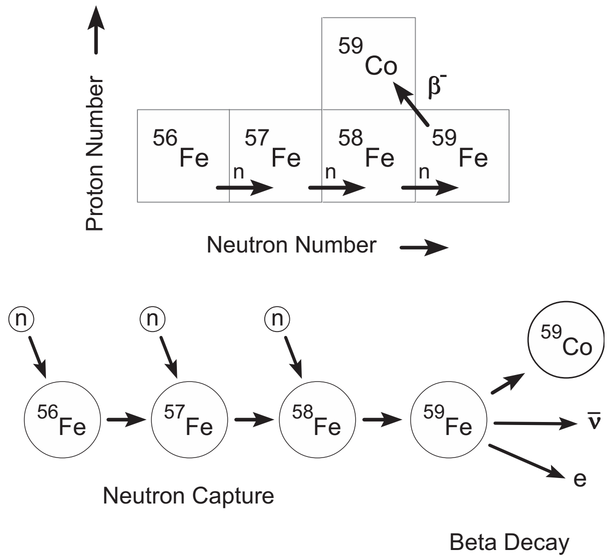


Figure 11.13: An example of slow neutron capture and β-decay in the s-process.

The s-process refers to a sequence of neutron capture reactions interspersed with beta decays to produce heavier elements where the rate of neutron capture is slow on a timescale set by competing beta decays.

- We can illustrate by considering an iron nucleus subjected to a low-intensity source of neutrons, as illustrated in Fig. 11.13.
- In this example, ^{56}Fe captures 3 neutrons sequentially to become ^{59}Fe.
- But as the iron isotopes become neutron rich they become increasingly unstable against β^- decay. In this example we assume that the neutron flux is such that ^{59}Fe is likely to beta decay to ^{59}Co before it can capture another neutron.



- Now the ^{59}Co nucleus can absorb neutrons and finally beta decay to produce an isotope of the next atomic number (nickel), and so on.
- By this process, heavier elements can be built up slowly if a source of neutrons and the seed nuclei (iron in this case) are available.

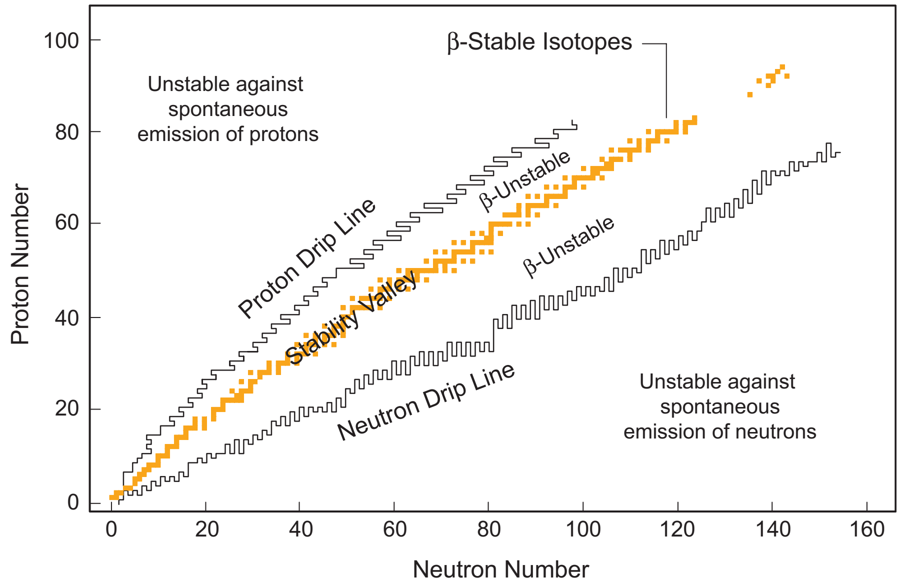


Figure 11.14: The valley of beta stability (shaded region). Isotopes lying in this valley are stable against β-decay. The "drip lines" mark the boundaries for spontaneous emission of protons or neutrons. Isotopes outside the stability valley are increasingly unstable against β-decay as one moves toward the drip lines.

- Because of the competition from beta decay, it is clear that the s-process can build new isotopes only in the *valley of beta stability* illustrated in Fig. 11.14.

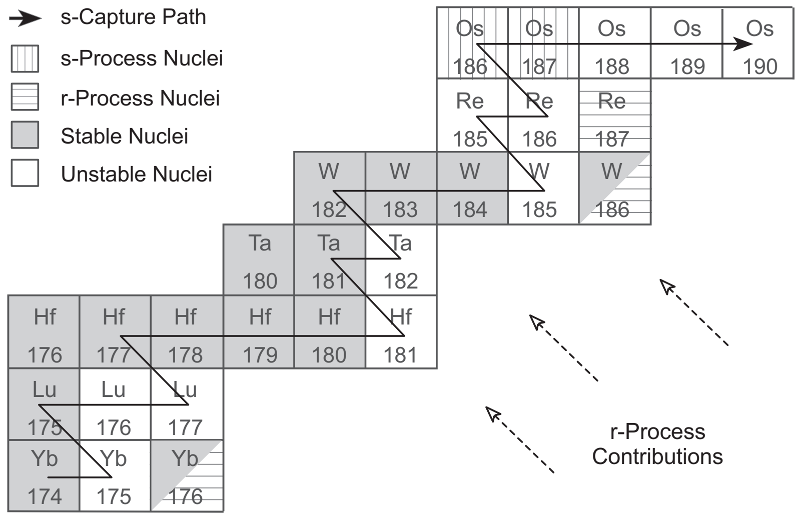


Figure 11.15: The s-process path in the Yb–Os region.

In Fig. 11.15 the s-process path is illustrated in the Yb–Os region.

- Notice that the path stays very near the stability valley (dark boxes).
- This figure also illustrates the competition between the s-process and r-process in producing the heavier elements.
- As we shall see, the r-process generally populates very neutron-rich isotopes that then β^- decay toward the stability valley.
- Some isotopes (for example, $^{186-187}$Os) can be populated only by the s-process because other stable isotopes protect them from r-process populations β-decaying from the neutron-rich side of the proton–neutron plane.
- Other isotopes (for example, ^{186}W) can be populated only by the r-process because an unstable isotope lies to their left in Fig. 11.15, blocking the s-process slow neutron capture path.

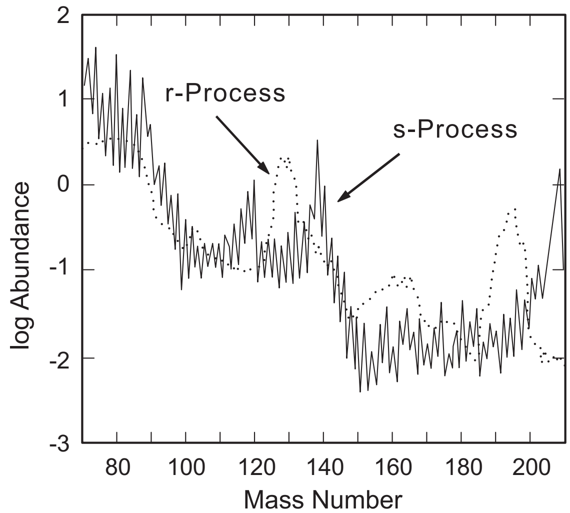


Figure 11.16: Relative contributions of the s-process and the r-process to heavy element abundances.

Many isotopes can be produced both by the s-process and the r-process. The relative contributions of the s-process and r-process to heavy element abundances are summarized in Fig. 11.16.

A source of slow neutrons is required for the s-process.

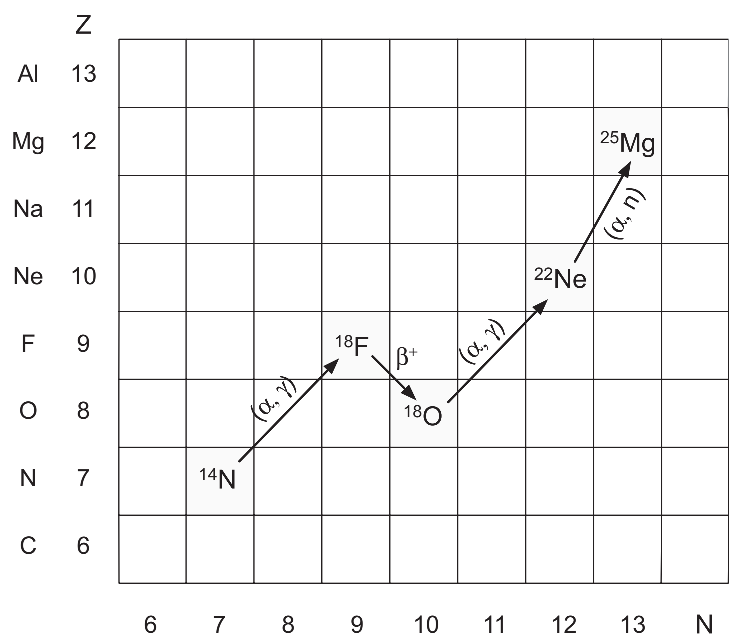
- Only a few nuclear reactions that are likely to occur in stars under normal conditions produce neutrons.
- Free neutrons are unstable against β-decay on a 10-minute timescale.
- Thus neutrons for the s-process are not easy to come by.

The box on the next page discusses possible neutron sources for the s-process that are thought to be present in red-giant stars during the AGB phase.

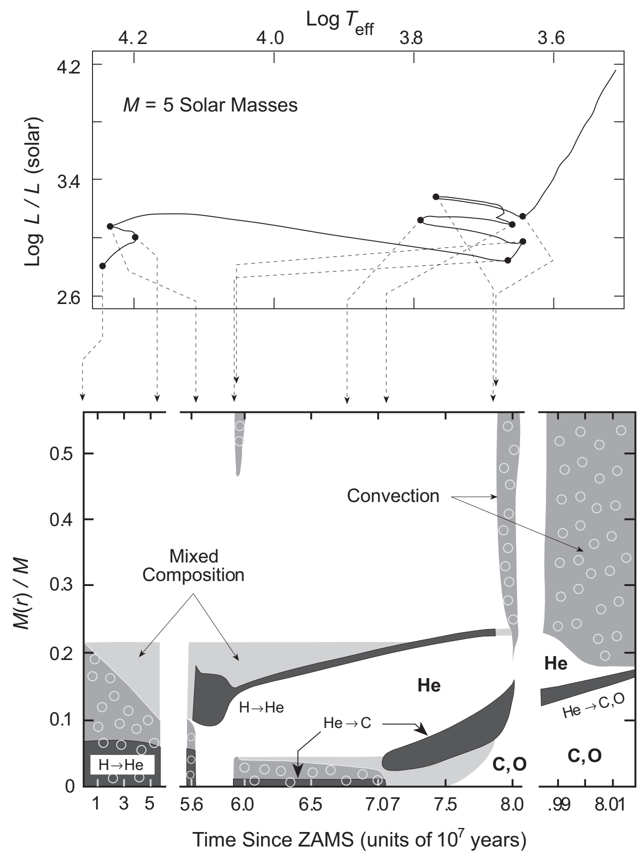
For the slow capture process it is thought that two reactions that can occur in AGB stars are primarily responsible for supplying the neutrons:

$$^{4}\mathrm{He} + {}^{13}\mathrm{C} \longrightarrow {}^{16}\mathrm{O} + \mathrm{n} \qquad {}^{4}\mathrm{He} + {}^{22}\mathrm{Ne} \longrightarrow {}^{25}\mathrm{Mg} + \mathrm{n}$$

- The most important reaction path leading to the $^{22}\mathrm{Ne}(\alpha, \mathrm{n})^{25}\mathrm{Mg}$ reaction is



- The $^{13}\mathrm{C}(\alpha, \mathrm{n})^{16}\mathrm{O}$ reaction is expected to provide the neutron flux at low neutron densities ($\lesssim 10^{7}\ \mathrm{cm}^{-3}$).
- The reaction $^{22}\mathrm{Ne}(\alpha, \mathrm{n})^{25}\mathrm{Mg}$ plays a secondary role, occurring at higher T during thermal pulses.



11.7.3 Development of Deep Convective Envelopes

- Once a thin helium shell source develops the resulting temperature gradients drive very deep convection extending down to the shell sources (above).
- As we shall discuss later, mixing associated with this deep convection is central to understanding the observation of nuclear-processed material associated with surfaces and winds for red giant stars.

11.7.4 Mass Loss

Observations indicate that once stars leave the main sequence they experience large mass losses, particularly in the AGB and RGB phases.

- This is most directly indicated by the observation of gas clouds with outwardly directed radial velocities of 5–30 $\mathrm{km\,s^{-1}}$ near such stars.
- It has been found that this mass loss is described by a semiempirical expression of the form

$$\dot{m} \simeq -A\frac{LR}{M}\,M_\odot\,\mathrm{yr}^{-1},$$

  where $A \sim 4 \times 10^{-13}$ is a constant, L is the luminosity, R is the radius, and M is the mass of the star.
- Thus, the rate of mass ejection increases linearly with larger luminosity, larger radius, and smaller mass.
- This would be expected for mass loss from the surface of a luminous object with a surface gravitational field determined by its mass and radius.

Therefore, on the RGB and AGB

- the rapid increase in radius and luminosity leads to increased mass loss, and
- as the star sheds its matter the decreased residual mass reduces the gravitational potential and further accelerates the loss.

Although the detailed mechanism is not well understood, it is clear empirically that the mass loss can increase by orders of magnitude relative to that associated with normal stellar winds in the RGB and AGB phases.

Example: For RGB stars mass losses of $10^{-6}\, M_\odot\,\mathrm{yr}^{-1}$ have been recorded, while for AGB stars the losses can approach $10^{-4}\, M_\odot\,\mathrm{yr}^{-1}$. If these rates were sustained, a red-giant star would eject all of its mass on a timescale that is tiny compared to its overall lifetime.

11.8 Ejection of the Envelope

In the AGB phase the envelope of the star is consumed both from within and without:

- The surface is ejecting mass, while the carbon–oxygen core is growing internally as the shell sources burn outward.
- Detailed estimates indicate that the *surface mass loss is more important by orders of magnitude.*

This rapid loss of the envelope primarily from surface ejection while the core grows at very small comparative rates has two important implications:

1. The envelope of the star is lost rapidly into space, leaving behind a carbon–oxygen core.
   - The rapid loss of the envelope implies that a range of initial masses will leave behind cores (white dwarfs) of *almost the same mass.*
   - This is significant because white dwarf masses are observed to be concentrated in a narrow range near $M \simeq 0.6\, M_\odot$.
2. The ejected envelope is a natural candidate for producing *planetary nebulae,* which are commonly observed phenomena in late stellar evolution.

Thus, we expect the primary outcome of AGB evolution to be the ejection of most of the star's envelope as a planetary nebula, leaving behind a bare C–O core that will cool to form a white dwarf.

11.9 White Dwarfs and Planetary Nebulae

Late in the AGB phase, mass loss increases dramatically for a short period called the *superwind phase* (which, as for other mass-loss phases, is not well understood).

- The radius decreases and the temperature increases, with the luminosity about constant.
- From this point onward it is useful to consider the evolution of the core and the envelope separately.

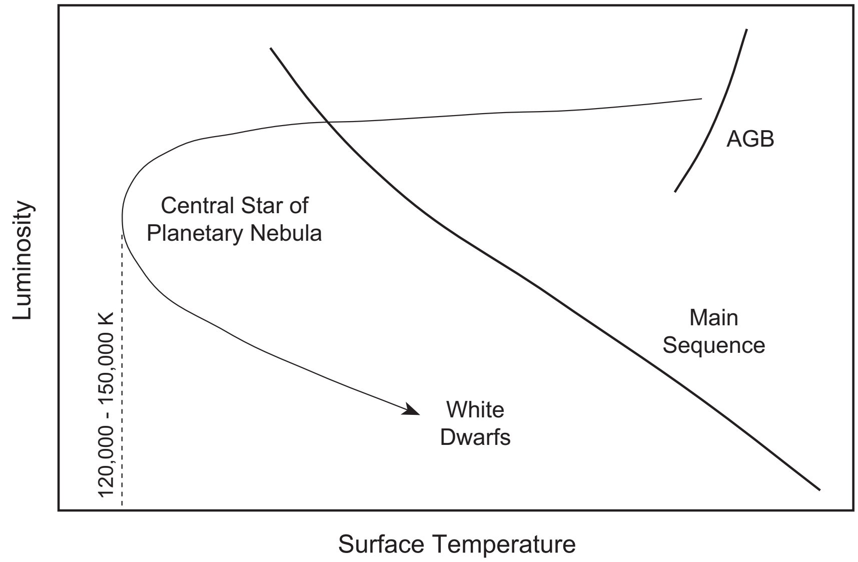


Figure 11.17: Evolution after the asymptotic giant branch.

As the core compresses, it follows the approximate evolutionary track shown in Fig. 11.17.

- This takes it to much higher temperatures than for the normal HR diagram.
- It finally cools to the white dwarf region with attendant decrease in luminosity.
- This high temperature is a result of
  - retained thermal energy
  - gravitational compression

  since the core is no longer capable of producing energy by thermonuclear processes.

- The remnants of the ejected envelope recede from the star.
- When the temperature of the bare core reaches about 35,000 K
  - a fast wind, probably associated with radiation pressure from the hot core, accelerates the last portion of the envelope to leave,
  - this forms a shock wave that proceeds outward and defines the inner boundary of the emitted cloud.
- As the temperature of the central star climbs, the spectrum is shifted far into the UV and this bath of high energy photons from the central star ionizes the hydrogen in the receding envelope.
- The resulting recombination reactions between ions and electrons emit visible light and account for the luminosity and the often beautiful colors associated with the planetary nebula.
- The core and the planetary nebula now proceed on their separate ways:
  - the core cools slowly to a white dwarf,
  - the planetary nebula expands and grows fainter, eventually merging into the interstellar medium.

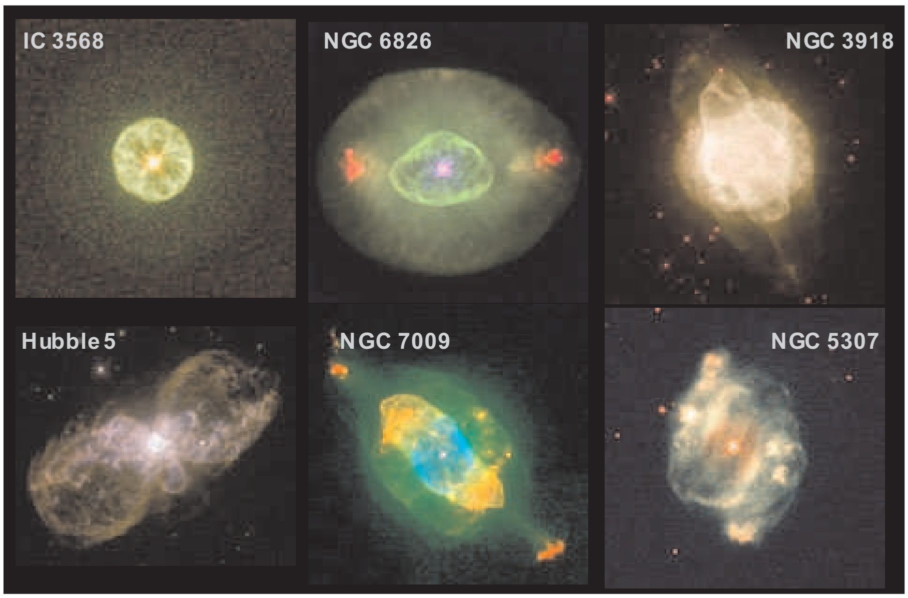


Figure 11.18: A variety of planetary nebulae imaged by the Hubble Space Telescope. Such observations indicate that the ways in which dying AGB stars eject their envelopes can be quite complex.

11.10 Stellar Dredging Operations

Various observations indicate that red giant stars exhibit abundances of isotopes in their surfaces and winds that could only have been produced by nuclear burning in the core and in shell sources.

- Since post main-sequence evolution in the red giant region involves various episodes of deep convection, it is logical to assume that the observed nuclear-processed material is brought to the surface by this deep convective mixing.
- This mechanism of transporting the products of nuclear burning and processing to the surface by deep convection is termed a *dredge-up*.

Three dredge-up episodes have been identified in post main-sequence evolution:

1. *First dredge-up* is thought to occur as the star develops deep convection driven by the hot hydrogen shell source prior to triple-α ignition on the red giant branch.

2. *Second dredge-up* can occur early in AGB evolution for intermediate mass main-sequence stars as a result of convective gradients generated by the narrowing helium shell source.

3. *Third dredge-up* is more difficult to produce in simulations than the first two but appears to be necessary to understand surface abundances for many evolved AGB stars. It is thought to be associated in a complex way with thermal pulses in AGB evolution, through deep convection that extends at least periodically into the region between the H and He shell sources

Although these dredge-up episodes are only partially understood, they are key to explaining observations like carbon stars (stars with a greater abundance of C than O in their surfaces) and the abundance of interstellar carbon dust grains.